Planet Formation and Exoplanets: Programming Assignment

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This assignment was completed using the PICASO exoplanet atmosphere modeling package Batalha et al. (2019).

Reflected Light Spectra of Cool Planets

1. When increasing the spectral resolution (R) of the albedo spectrum, the spectra becomes noisier and finer details become visible (Figure 1.). In other words, you can distinguish between lines that would otherwise be overlapping at lower resolutions. Seeing more lines as you increase spectral resolution means that there are more molecular species present in the atmosphere than perceived initially. The overall opacity of the atmosphere is composed of numerous different molecules.

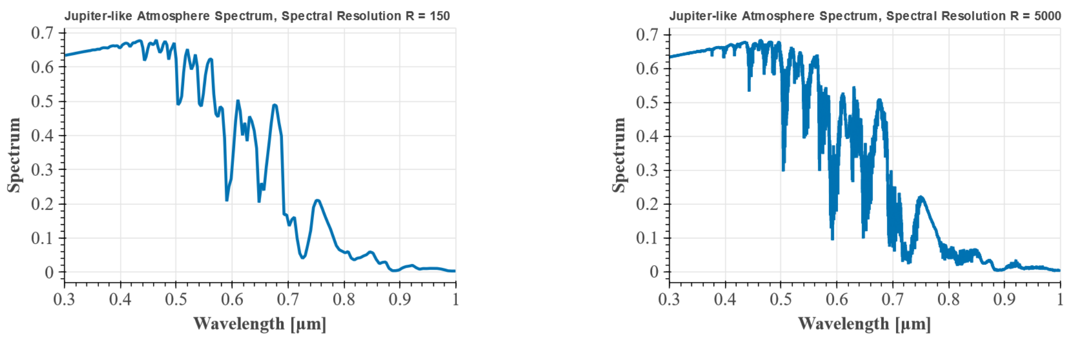


Figure 1: Two figures depicting the spectrum of a Jupiter-like atmosphere in 0.3 to 1.0 micron with a spectral resolution of 150 on the left, and 5000 on the right. Albedo is measured on the y-axis.

2. When analyzing which molecules commonly found in the atmospheres of cold giant planets are the dominant sources of opacity for this model atmosphere, only a few appear to carry much influence. When looking at figure 2, H_2O or water appears to be the most dominant source of opacity as the spectra changes considerably when excluding this molecule. CH_4 or Methane has only a small effect on the opacity, while NH_3 or ammonia, CO or carbon monoxide, and CO_2 or carbon dioxide provides minimal contribution to the opacity.

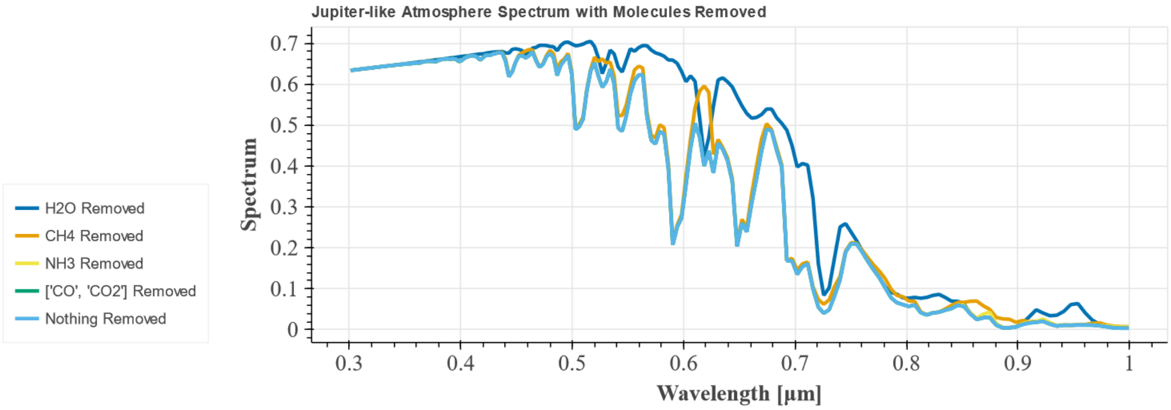


Figure 2: Figure depicting multiple variations of the same spectrum of a Jupiter-like atmosphere in 0.3 to 1.0 micron with certain molecules removed. Spectral resolution is 150. Albedo is measured on the y-axis.

3. Simple clouds are now added to the model atmosphere (figure 3). The variables governing the characteristics of the cloud include: the asymmetry factor (g0), single scattering albedo (w0), total extinction (opd), pressure level (p) in log10 bars, and cloud thickness (dp) in log10 bars. The asymmetry factor is a property of a scattering medium such as a cloud of molecules; particles that are small compared to the wavelength of the incident radiation possess an asymmetry factor close to zero, while larger particles will be closer to one. The single scattering albedo is a ratio of the scattering coefficient to the extinction coefficient. Typically, for much of the visible spectrum, this factor will be close to one for clouds. Total extinction refers to the opacity. Finally, pressure level is the maximum cloud pressure, and cloud thickness is just the cloud thickness.

   In figure 4, various cloud models are plotted against the simple clouds model, each variation has a single characteristic variable changed to investigate how these variables effect the resulting spectra. Upon analyzing these plots, a couple trends are noticed. As the asymmetry factor increases, the spectra lines become more defined, and the albedo appears to decrease slightly. Similarly, as the single scattering albedo increases, the spectra lines become more defined, however the albedo increases. With opacity, something interesting occurs in that albedo significantly increases at low opacity and the spectra narrows, while at high opacity the albedo drops and the spectra broadens. This could be due to the composition of the model atmosphere, or a combination with the fact that high opacity means stronger absorption, therefore less reflectivity. As the maximum cloud pressure increases, the amplitude of the spectra appears to increase slightly. However, as the cloud thickness decreases, albedo significantly increases.

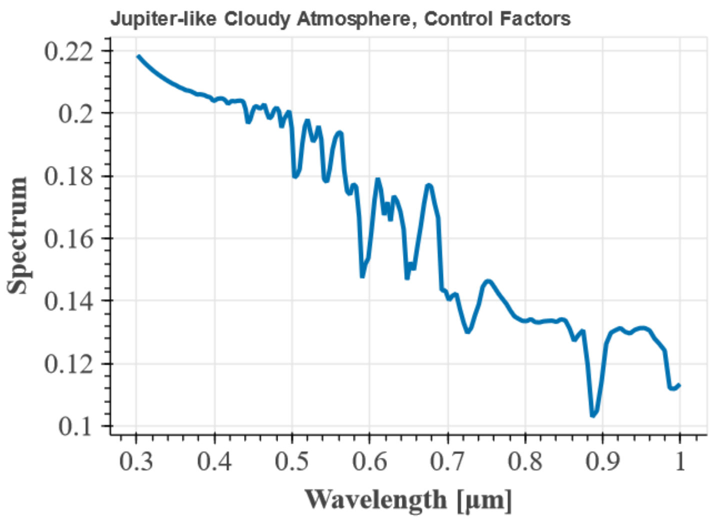


Figure 3: Figure depicting the spectral line of the model Jupiter-like atmosphere in 0.3 to 1.0 micron with simple clouds added. For this model, the variables were set as follows: g0 = 0.9, w0 = 0.8, opd = 0.5, p = 0.0, and dp = 1.0. Albedo is measured on the y-axis.

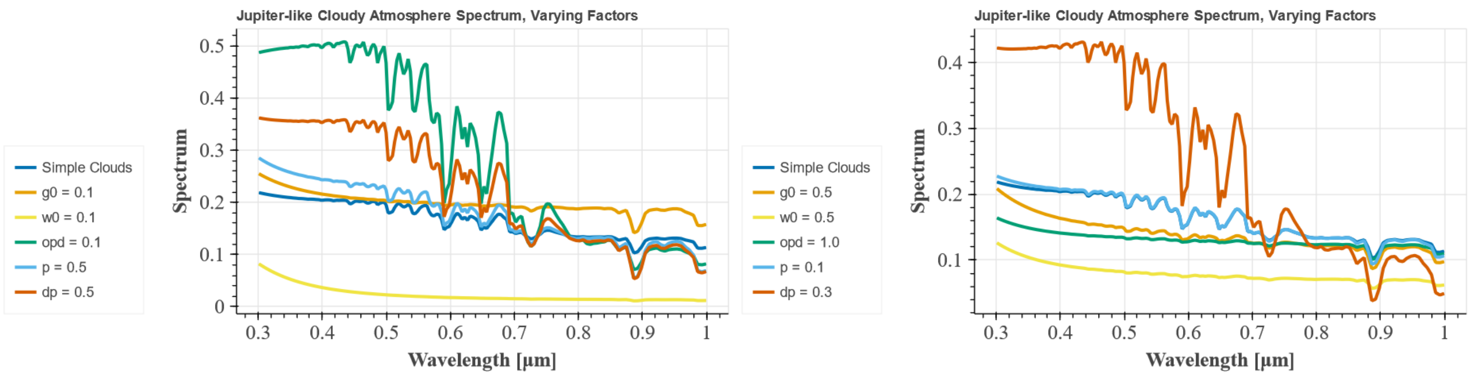


Figure 4: Figures depicting multiple spectral lines of the model Jupiter-like atmosphere in 0.3 to 1.0 micron with various clouds added. In each plot, the simple cloud from figure 3 is included alongside variations of the simple cloud model, each with one variable changed from the simple cloud model as noted in the legend. Albedo is measured on the y-axis.

4. When looking at the effect the different cloud characteristics have on the spectra model in figure 4, a few degeneracies amongst the variables are noticed. For instance, decreasing opacity appears to share the same effect as decreasing the cloud thickness in raising the albedo of the spectra and narrowing spectra lines. This could mean cloud thickness is an alternative way of defining opacity, as a thick cloud would absorb more radiation, thereby decreasing reflectivity. Another trend is that the asymmetry factor and single scattering albedo values appear to complement eachother. For both values, the spectra narrows and gains definition as the values increase. However as the asymmetry factor increases, albedo decreases which is the opposite case for increasing single scattering albedo. From this, one can infer each variable for the cloud model has its own function yet each variable can be tuned a certain way where spectra can be recreated with a different set of variables.

Transmission Spectra of Warm Planets

5. The transmission spectrum for a hot Jupiter model atmosphere in the wavelength range accessible with the NIRSpec instrument onboard the James Webb Space Telescope (0.6 - 5 micron) is plotted in figure 5.

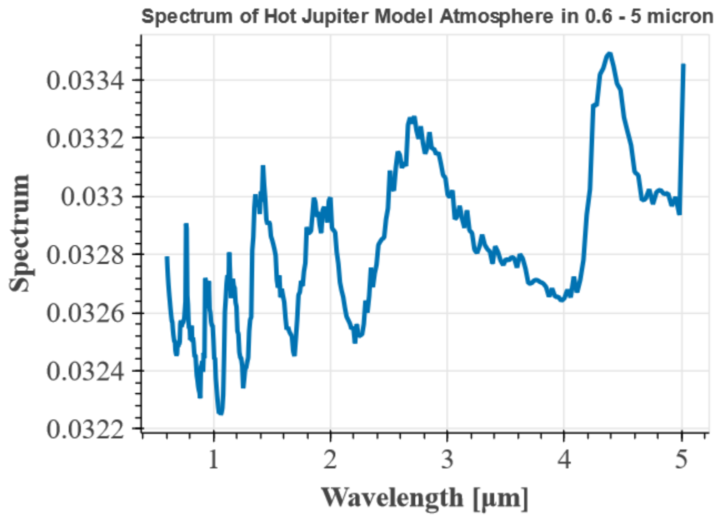


Figure 5: The transmission spectrum for a hot Jupiter model atmosphere in 0.6 to 5.0 micron, the wavelength range accessible with the NIRSpec instrument aboard JWST. Transit depth is measured on the y-axis.

6. When investigating figure 6, a few molecular species can be seen contributing significantly to the opacity of the hot Jupiter model atmosphere. Namely, water, K or potassium, carbon dioxide, and methane. Overall, removing water from the spectrum had the largest impact as the transit depth was significantly lowered for most of the wavelength range. This means less radiation was absorbed, lowering transit depth, thereby demonstrating water accounts for a significant portion of the opacity. Removing potassium appeared to lower the transit depth only for the wavelengths below 1 micron. Removing carbon dioxide had a noticeable influence in transit depth between 2 and 3 microns and an even larger influence between 4 and 5 microns. Removing methane had the smallest effect between 3 and 4 microns. Otherwise, removing sodium appeared to have little to no effect.

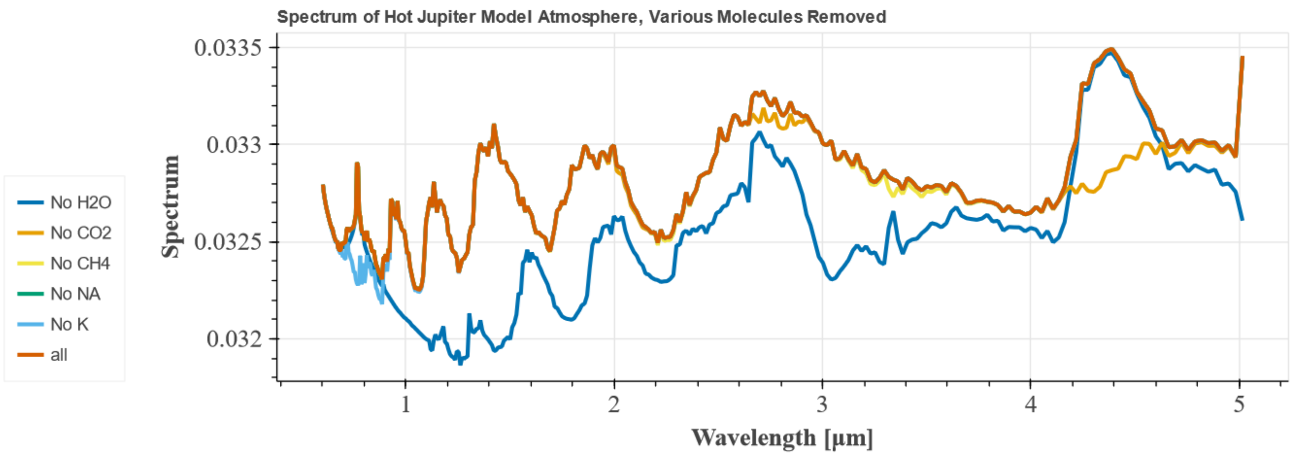


Figure 6: Figure depicting multiple variations of the same transmission spectrum of a hot Jupiter atmosphere in 0.6 to 5.0 micron with certain molecules removed. Transit depth is measured on the y-axis.

7. In figure 7, as planetary mass increases and therefore gravity increases, a couple differences can be seen between spectral lines. As gravity increases, the spectral lines broaden and the transit depth decreases. Spectra broadening makes sense as higher atmospheric pressure will occur as gravity increases, which can lead to pressure broadening since more molecular collisions will occur and with higher energies. The transit depth decreasing with gravity increasing also makes sense since as gravity increases, the atmosphere of the planet will contract under the pressure of gravity. Therefore, less light will be blocked when the planet passes in front of its host star.

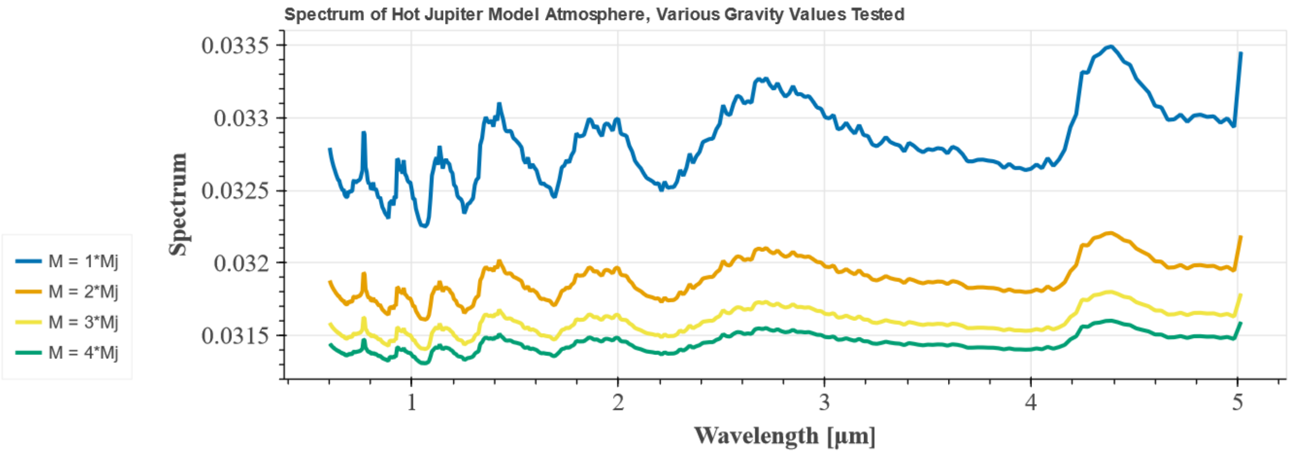


Figure 7: Multiple spectral lines of hot Jupiter model atmosphere in 0.6 to 5.0 micron with varying masses of planet in Jupiter masses. Mass is varied to investigate effect of gravity on spectral lines as value for gravity cannot be directly changed in code. Transit depth is measured on the y-axis.

8. A simple model of gray (wavelength independent) clouds are added to the hot Jupiter atmosphere (figure 8). The mean transit depth of the spectra with gray clouds added appears to decrease compared to the spectra without gray clouds. Additionally, the amplitude of the gray cloud spectra is also less than the cloud free spectra. The gray cloud spectra is also missing the deep dips that are present in the cloud free spectra. This makes sense since clouds can absorb and scatter incoming radiation, thereby reducing the intensity of the observed radiation.

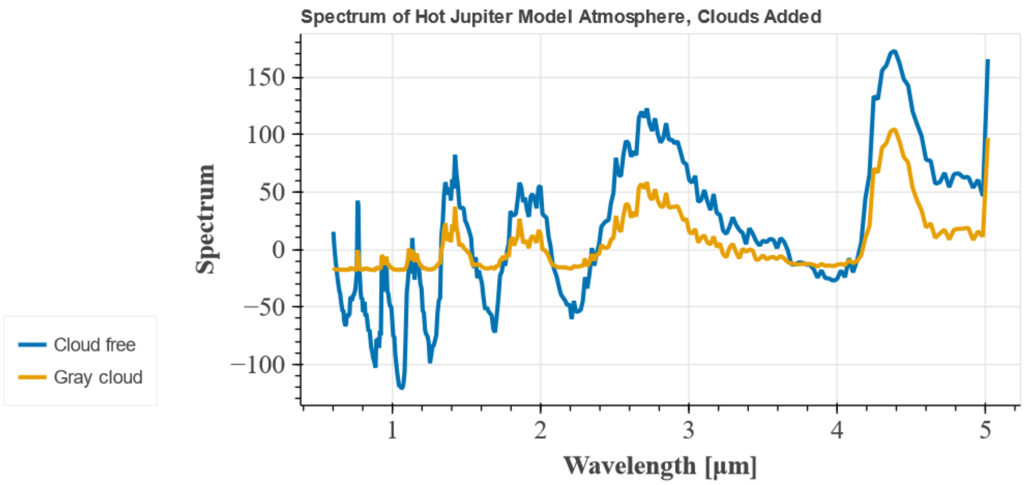


Figure 8: The transmission spectrum for a hot Jupiter model atmosphere in 0.6 to 5.0 micron with gray (wavelength independent) clouds added. The cloud properties are as follows: p = 1.0, dp = 4.0, opd = 1.0, g0 = 0.0, w0 = 0.0. Transit depth is measured on the y-axis.

Thermal Emission Spectra of Warm Planets

9. The thermal emission spectrum for a hot Jupiter model atmosphere in the NIRspec wavelength range (0.6 to 5.0 micron) can be seen in figure 9.

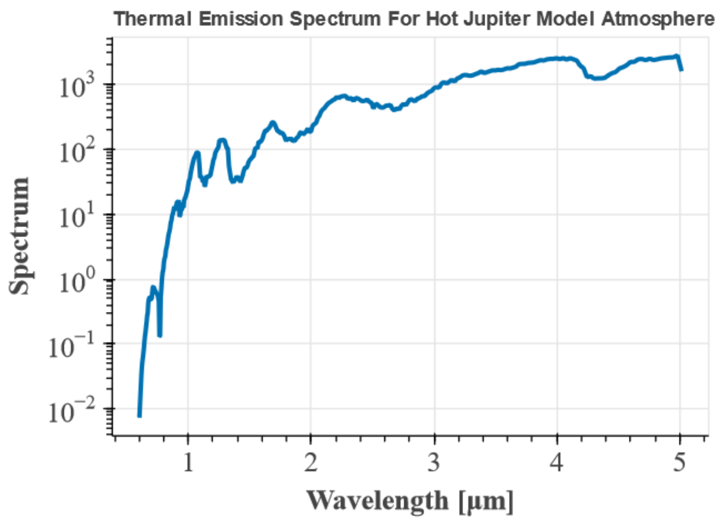


Figure 9: The thermal emission spectrum for a hot Jupiter model atmosphere in 0.6 to 5.0 micron. Log10 of relative thermal flux is measured on the y-axis.

10. According to figure 10, a blackbody temperature range of roughly 1075 K to 1435 K is a reasonably good match to the underlying continuum of the spectrum in question. This relates to a pressure range of 0.01 bars to 0.5 bars respectively.

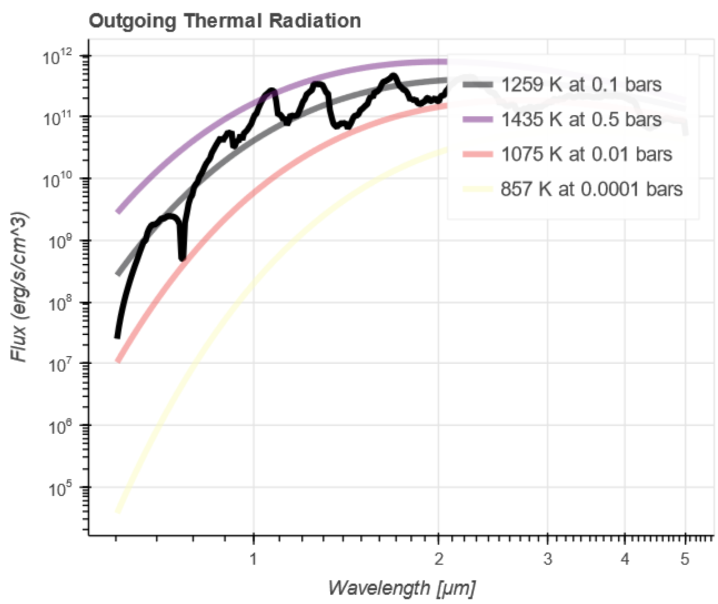
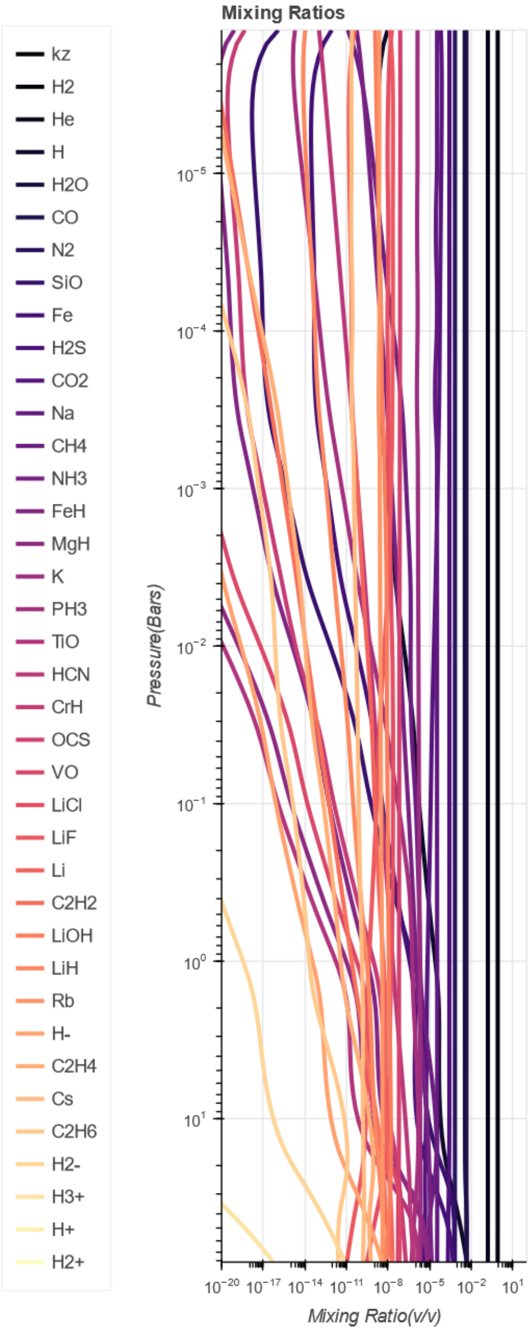


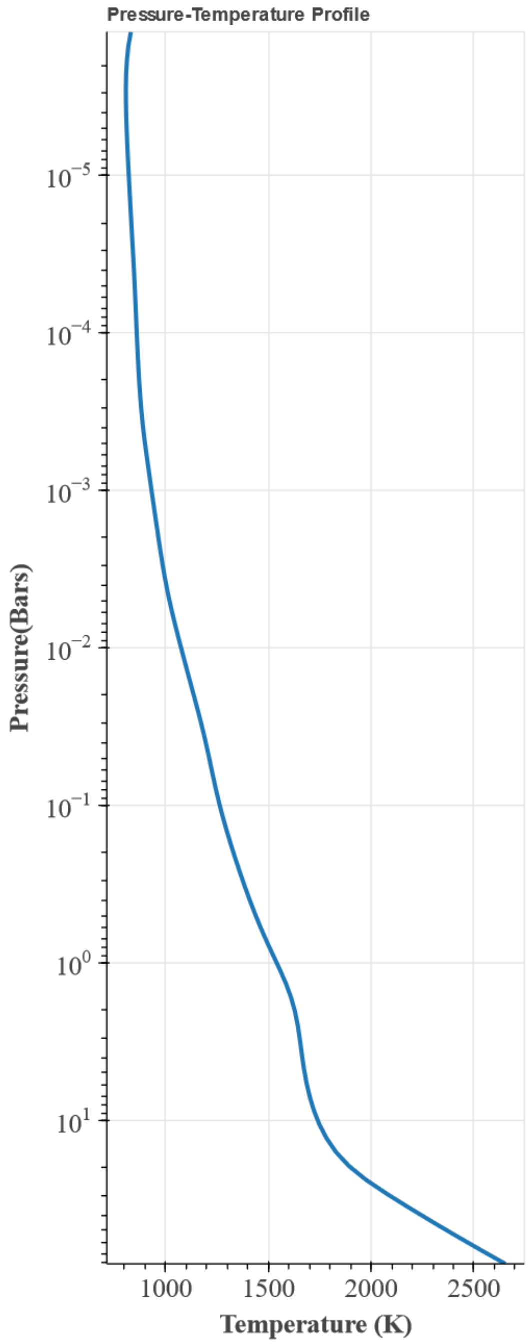
Figure 10: Plot of the computed flux and blackbodies of temperatures at various pressures along the pressure-temperature profile of hot Jupiter model atmosphere (black) in 0.6 to 5.0 micron. Log10 of relative thermal flux is measured on the y-axis.

11. When applying the pressure range found previously (0.01 bars to 0.5 bars) to the two subplots in figure 11, the composition of the atmosphere in this pressure range can be seen. According to the legend in figure 11. a., this includes H2 with the largest mixing ratio, to Cs as with the smallest. The molecules present in this pressure range are as listed from largest mixing ratio to least: H2, He, H, H2O, CO, N2, SIO, Fe, H2S, CO2, Na, CH4, NH3, FeH, MgH, K, PH3, TiO, HCN, CrH, OCS, VO, LiCl,

LiF, Li, C2H2, LiOH, LiH, Rb, H-, C2H4, and Cs.
In figure 11 a., the pressure in the y-axis decreases upwards. This is representative of the atmospheric altitude since pressure towards the surface of the planet will be higher compared to the pressure in the upper layers of the atmosphere. From this figure, we can see some molecules "trail off" towards the left as their mixing ratio decreases with altitude. Other molecules, such as H_2 remains constant throughout. This demonstrates how the atmospheric composition becomes less diverse with altitude as the environment becomes less hospitable for certain molecules.



(a) The relative abundances (mixing ratios) of different molecular species as a function of pressure level in the hot Jupiter model atmosphere.



(b) The pressure-temperature profile of the hot Jupiter model atmosphere.

Figure 11

References

Batalha N. E., Marley M. S., Lewis N. K., Fortney J. J., 2019, The Astrophysical Journal, 878, 70